A Study on Effects of Recirculated Exhaust Gas upon Wear of Cylinder Liner and Piston in Diesel Engines

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The effects of recirculated exhaust gas on the wear of cylinder liner and piston were experimentally investigated by a two-cylinder, four cycle, indirect injection diesel engine operating at 75% load and 1600 rpm. For the purpose of comparison between the wear rates of the two cylinders with and without EGR, the recirculated exhaust gas was sucked into one of two cylinders after the soot in exhaust emissions was removed by an intentionally designed cylinder-type scrubber equipped with 6 water injectors (A water injector has 144 nozzles of 1.0 mm diameter), while only the fresh air was inhaled into the other cylinder. These experiments were carried out with the fuel injection timing fixed at 15.3° BTDC. It was found that the mean wear rate of cylinder liner with EGR was greater in the measurement positions of the second half than those of the first half, that the mean wear rate without EGR was almost uniform regardless of measurement positions, and that the wear rate of piston skirt with EGR increased a little bit, but the piston head diameter increased, rather than decreased, owing to soot adhesion and erosion wear, and especially larger with EGR.

Key Words : EGR (Exhaust Gas Recirculation), Cylinder Liner, Diesel Engine, Wear Rate, Piston Skirt and Head, Soot Adhesion, Erosion Wear

1. Introduction

Recently atmospheric environment has been heavily polluted by exhaust gases emitted from combustion engines. Since problems of air pollution are mainly attributed, in particular, to exhaust emissions of diesel engines, there have been many research efforts among the concerned industries and institutions to work on solutions to reduce hazardous emissions from diesel engines. (Bae, 1989 ; Bae and Kim, 1994) One of these measures to reduce NO_x emissions is EGR method, which produces a remarkable NO_x reduction effect. It is well documented, however, that EGR may increase other exhaust emissions, fuel consumption rate and the wear of engine components such as the cylinder liner, piston and other parts. In spite of these disadvantages, on the other hand, many researchers have been trying to apply the EGR system in a diesel engine because there are virtually no other better measures for NO_x emissions reduction without a special reconstruction of engine. (Arcoumanis *et al*., 1995 ; Bae, 1999 ; Bae *et al*., 1999 ; Bae et al., 2000)

Bae *et al*. (1999a, 1999b) have conducted experiments with EGR system mounted on a diesel engine in order to investigate its effect on exhaust emissions and fuel consumption rate, with the result that increased EGR rate at a high load and high speed led to excessive soot emissions, rendering the operation impractical. As an alternative, Bae (1999a) have reported a substantial soot reduction effect by applying an

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exhaust gas recirculating system with scrubber that fed soot-removed exhaust gas back into the diesel engine.

In EGR application, the major research targets with regard to its effect on the wear increase are; increased soot amount adhered onto oil film (Shiozaki *et al*., 1989 ; Gautam *et al*., 1999) ; sulfuric contents contained in fuel (Hiroyuki and Koji, 1993, 1994 ; Tani and Sunada, 1994), and so on. While earlier studies were largely focused on abrasive wear due to soot (Shiozaki *et al*., 1989), recent studies have been devoted mostly to the study on wear due to SO_x such as the deterioration of lubricating oil by SO_x in recirculated exhaust gas (Furuhama *et al*., 1991) and the breaking of oil film due to H_2SO_4 generated from SO_x (Murakami, 1993). 97~98% of sulfuric contents contained in fuel react with oxygen during combustion to make SO_2, which is emitted included in exhaust gas. When EGR system is applied to recirculate some of the exhaust gas into the cylinders, the generated SO_2 oxidizes into SO_3, which reacts with water to make H_2SO_4. At a relatively low temperature (400~420 K), this H_2SO_4 precipitate is formed around soot particles serving as nuclei and adheres to engine components such as the cylinder liner, piston and so on, thereby eroding their surfaces (erosion wear). The resultant rough, eroded surfaces are rubbed against abrasive powder, oxide compound of lubricating oil and soot in operation, producing further wear (abrasion wear : Shiozaki *et al*., 1989).

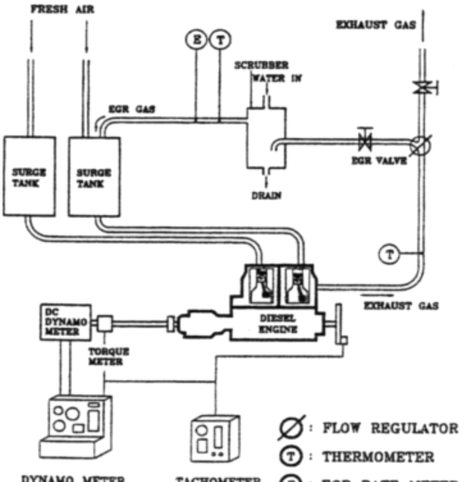


Fig. 1 Schematic diagram of experimental apparatus

In the present study, no attempt was made to identify causes of increased wear amounts. Instead, to understand an intrinsic nature of EGR, the effects of the soot and SO_x emissions in recirculated exhaust gas on the wear of cylinder liner and piston were experimentally investigated on a diesel engine with EGR application. And the findings may be utilized as preliminary data for designing and developing a feasible control device of the practical EGR system in diesel engines.

2. Experimental Apparatus and Techniques

2.1 Experimental apparatus

The schematic diagram of experimental apparatus is shown in Fig. 1. The test engine employed in the present study was a four cycle, two-cylinder, water-cooled, indirect injection, marine diesel engine manufactured in Korea. The major specifications of the engine are presented in Table 1.

To investigate the effects of recirculated exhaust gas on the wear of cylinder liner and piston, No. 1 cylinder of the two cylinders was fed with air passed through the surge tank. While No. 2 cylinder was fed with the intake mixture of fresh air and recirculated exhaust gas of a 20% EGR rate. The exhaust gas was passed through a novel diesel soot-removal device with a cylinder-type scrubber and entered into the surge tank to minimize the surging.

Table 1 Specifications of test engine

Items	Specifications
Type	2 Cylinder, Water-Cooled, 4 Cycle, Indirect Injection, Natural Aspiration
Piston Displacement (cc)	1630
Bore (mm) × Stroke (mm)	95 × 115
Maximum Power	14.71 kW/1800 rpm
Fuel Injection Timing	BTDC 15.3°
Compression Ratio	20:1

The cross-section of a novel diesel soot-removal system with a cylinder-type scrubber that was designed and manufactured to eliminate soot contents from the recirculated exhaust gas is presented in Fig. 2. The exhaust gas emitted from the diesel engine is directed into the inlet port in the lower side of the scrubber and then passes through the disturbed rings before the soot is removed by water sprayed from 144 nozzle holes of 1 mm in diameter. The amount of sprayed water is automatically controlled by a flow meter with a solenoid valve according to EGR rate. In this study, however, the amount was constantly fixed since only a 20% EGR rate was applied. The resultant soot-removed exhaust gas is passed through the demister for dehydration and is flowed into the surge tank through outlet port, where it is mixed with the incoming fresh air.

A discharging port was installed in the lower part of the scrubber in order to prevent the sprayed water from flowing over the inlet. And a baffle plate was also installed on the floor of the scrubber to keep the incoming exhaust air from escaping directly into the discharging port.

The performance of the water injection device used in this study has been mentioned in previous work (Bae, 1999) ; where it was found that soot-removal efficiency without EGR application was approximately 30~50%, though it was variable depending on engine load levels. Thus this device

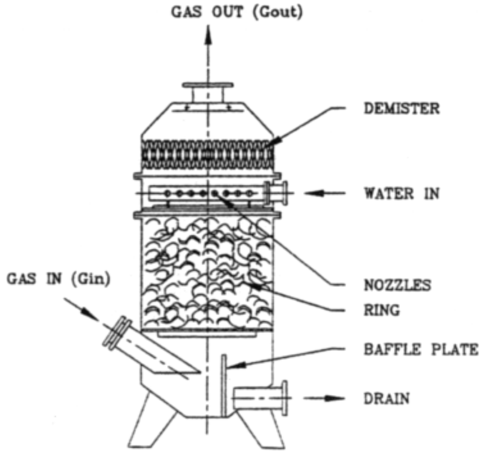


Fig. 2 Cross-section of a novel diesel soot-removal system with a cylinder-type scrubber

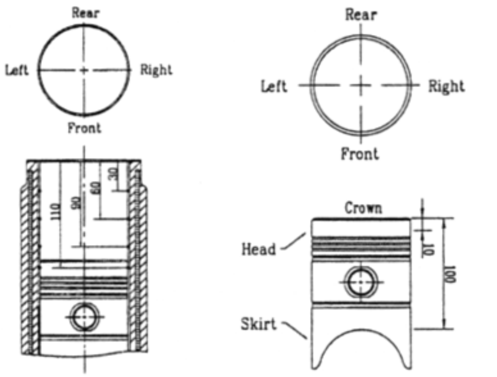
may be recommended as a method for soot removal in diesel engines with EGR system.

2.2 Experimental techniques

The engine was operated for 400 hours at an engine load of 75% and an engine speed of 1600 rpm, with or without EGR, in order to measure the wear rates of cylinder liner and piston as affected by the two conditions. Though the engine load, speed and EGR rate were fixed throughout the experimental period, the following variations were observed during the 400 hour engine operation: ±5% for engine load; ±1% for engine speed; and ±10% for EGR rate.

A water-cooling heat exchanger was employed to keep the temperature of lubricating oil between 333~343 K. K type thermocouples as temperature sensor were installed into the inlet and outlet of cooling water to control the temperature between 313~323 K, and then to check regularly the engine operation and combustion. Another K type thermocouple was installed in the exhaust pipe to measure exhaust gas temperature; 553~573 K was the adequate operating range. Fuel injection time was fixed at 15.3° BTDC. In general, the EGR rate is calculated by measuring the CO_2 concentrations at intake and exhaust manifolds (Bae, 1999 ; Bae *et al.*, 1999), but the present study calculated the EGR rate as the ratio of exhaust gas amount recirculated through EGR valve to total intake mixture amount (Narusawa *et al.*, 1990 ; Arcoumanis *et al.*, 1995).

In order to measure the wear amount of cylinder liner inner diameter after the experiment, the engine was disassembled prior to it. The inner diameter of cylinder liner was measured at intervals of 90° rotated positions with distances of 30, 60, 90 and 110 mm from the top; A bore gauge was used for these measurements. The measurement positions are shown in Fig. 3(a). This gauge has a measurement range of 50~100 mm and a minimum scale of 1 μm. For the outer diameter of piston, a digital micrometer was used to take measurements of the head part 10 mm away from the piston crown and the skirt part 100 mm away from the piston crown, as shown in Fig. 3(b). The micrometer has a measurement range of



(a) Cylinder Liner (b) Piston

Fig. 3 Measurement spots of cylinder liner and piston

75~100 mm, with a minimum scale of 1 μm. To distinguish the right-left and front-rear of measurement spots, the position located in piston pin hole was defined as a front spot for the measurements. The right spot was decided as the point 90° rotated counterclockwise from the front.

3. Results and Discussion

3.1 Wear rate of cylinder liners

The inner diameters of the cylinder liners were measured on No. 1 (with fresh air only) and No. 2 (with an EGR rate of 20%) cylinders as mentioned above. Figure 4 shows the measured values of the inner diameters obtained at a right-left spot with and without EGR before and after experiments, and a comparison between the wear rates of measured spots. As compared with measurements before experiments, the cylinder liners were found to have increased wear amounts regardless of EGR application; with higher wear amounts in case of EGR. In particular, the wear amounts with EGR were considerably higher than those without EGR at 90 and 110 mm from the top. Based on the above data, all the measured wear amounts were converted by defining the spot without EGR 30 mm away from the top as a wear rate of 100%. The relative percentage of the measurement is presented in Fig. 4, where it is shown that in no EGR condition, spots closer to the top produced higher wear rate, and that in

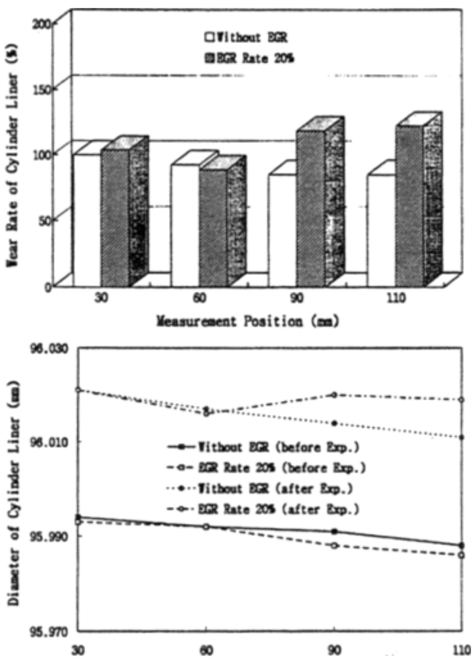


Fig. 4 Wear rate and inner diameter of cylinder liner for a right-left spot at the respective positions measured from the top

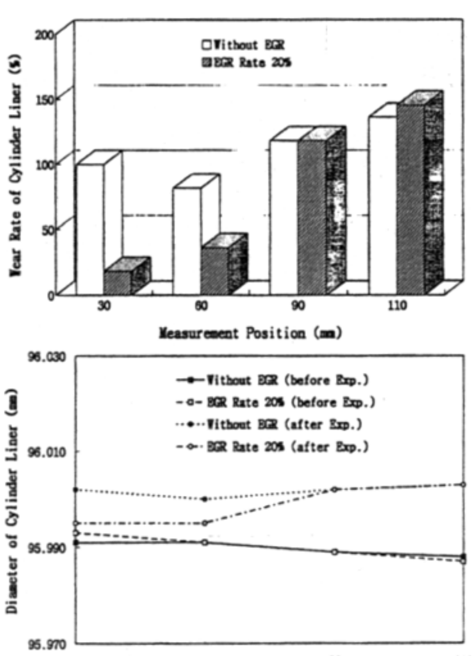


Fig. 5 Wear rate and inner diameter of cylinder liner for a front-rear spot at the respective positions measured from the top

case of EGR, distances greater than the spot 60 mm away from the top had higher wear rate, with the highest wear rate at 110 mm from the top in this study.

Figure 5 shows the measured values at a front-rear spot and the wear rate of a relative percentage in the same way mentioned above. This figure indicates that the wear rate with EGR was lower than that without EGR up to the spot 90 mm away from the top, and that the wear rate due to EGR application grew higher at closer distances to the second half part.

Figure 6 shows the mean wear rate for right-left and front-rear spots. As can be seen from the figure, the wear amount without EGR was greater than that with EGR up to the spot 60 mm away from the top. Longer distanced spots than 60 mm, however, produced higher wear amount for applying EGR. The relative wear rate for the spot measurement is also shown in Fig. 6, where the first half beginning from the cylinder top showed

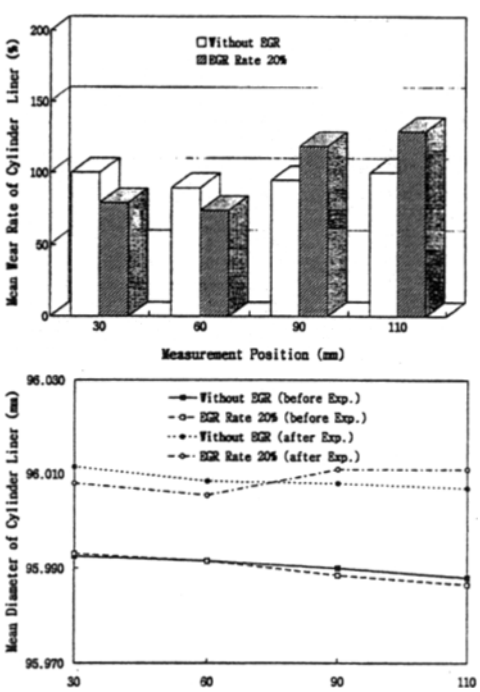


Fig. 6 Mean wear rate and inner diameter of cylinder liner for two spots of right-left and front-rear at the respective positions measured from the top

higher wear rate in no EGR than that with EGR application, and the wear rate with EGR was greater in the second half. In particular, No. 1 cylinder without EGR showed a similar wear rate regardless of the measuring positions, though showing slight variations. No. 2 cylinder with EGR showed a significantly higher wear rate in the second half than in the first half.

Shiozaki *et al.* (1989) have conducted a special simulation mode operation applying an EGR rate of 20% to investigate the wear rate of cylinder liner and piston rings on a in-line, six-cylinder (13.3 *l*), direct injection, heavy-duty diesel engine with JIS No. 2 light oil. They have shown that approximately four times higher wear rate was observed in case of EGR. They attributed this result to erosion due to H_2SO_4 and abrasion by particulate such as grinding powder and soot.

3.2 Wear rate of piston

The wear amounts of piston at the right-left spots of the head part 10 mm away from the piston crown and the skirt part 100 mm away from the piston crown were measured before and after the experiment. And all the measured wear amounts were converted into relative percentages by defining the piston skirt spot without EGR as a wear rate of 100%. Table 2 indicates the outer diameters of piston head and skirt measured before and after the experiment to calculate the wear amounts of two cylinders at a right-left spot.

Figure 7 shows the measured values of piston outer diameter and the wear rate. As can be seen from the figure, the skirt part at a right-left spot produced somewhat higher wear rate in case of EGR application, but the head part showed

Table 2 The outer diameters of piston head and skirt measured before and after the experiment to calculate the wear amounts of two cylinders at a right-left spot

	Piston Head		Piston Skirt	
	No. 1 Cyl. (No EGR)	No. 2 Cyl. (EGR)	No. 1 Cyl. (No EGR)	No. 2 Cyl. (EGR)
Before Exp. (mm)	95.151	95.150	95.712	95.713
After Exp. (mm)	95.175	95.219	95.654	95.645
Wear Amounts (mm)	−0.024	−0.069	0.058	0.068

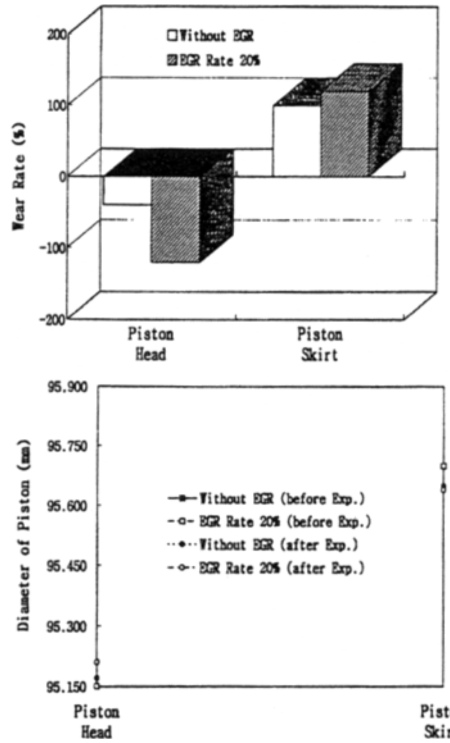


Fig. 7 Wear rates and outer diameters of piston head and skirt for a right-left spot at the respective measured positions away from the crown

increase in piston diameter regardless of EGR application, especially higher in case of EGR application. This peculiar result suggests the possibility that though the piston head suffered from significant wear, the roughened piston due to soot and other matters adhered to a piston surface or erosion by H_2SO_4 may have contributed to apparent piston diameter increase. In this experiment, a part of the roughened piston surface was wiped off by a scraper, but complete wiping could have caused a severe damage to the piston, making exact measurements impossible. As a solution to this problem, the increased and decreased amounts of the measured values were marked with − and + respectively to represent them in percentage.

Table 3 indicates the outer diameters of piston head and skirt measured before and after the experiment to calculate the wear amounts of two cylinders at a front-rear spot. Figure 8 shows

Table 3 The outer diameters of piston head and skirt measured before and after the experiment to calculate the wear amounts of two cylinders at a front-rear spot

	Piston Head		Piston Skirt	
	No. 1 Cyl. (No EGR)	No. 2 Cyl. (EGR)	No. 1 Cyl. (No EGR)	No. 2 Cyl. (EGR)
Before Exp. (mm)	95.152	95.151	95.844	95.862
After Exp. (mm)	95.178	95.210	95.791	95.807
Wear Amounts(mm)	−0.026	−0.059	0.053	0.055

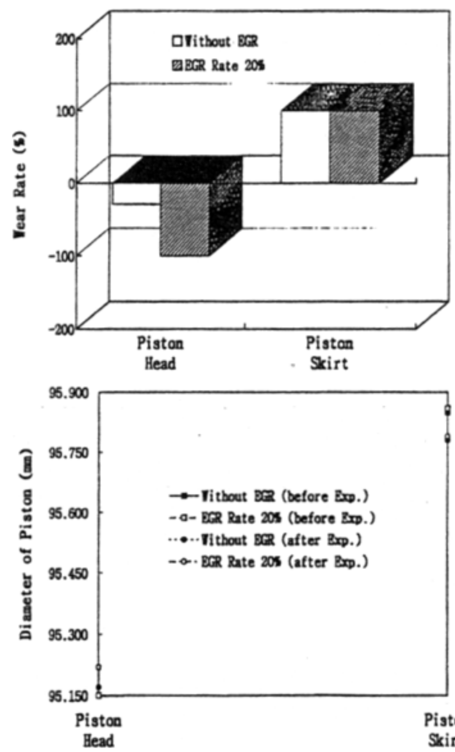


Fig. 8 Wear rates and outer diameters of piston head and skirt for a front-rear spot at the respective measured positions away from the crown

relative percentages of piston wear amounts at a front-rear spot, where the wear amount of the piston skirt part without EGR was defined as 100%. It can be seen that the skirt part showed nearly identical wear rates regardless of EGR application, but the head parts did show increase in piston diameter after the experiment, in particular in case of EGR application. It should be also considered that the reason that the wear rate of skirt part at a front-rear spot was identical regardless of EGR may have been due to the adhesion of soot and the erosion by H_2SO_4 on a piston surface as discussed previously even though the skirt part may be worn away by applying EGR.

The mean outer diameters of piston head and skirt measured before and after the experiment to calculate the wear amounts of two cylinders at two spots of front-rear and right-left are shown in Table 4. Figure 9 presents the mean wear rates and piston outer diameters of Fig. 7 and 8. The skirt parts showed a slightly higher wear rate in case of EGR application, while the head parts showed a remarkably higher piston diameter increase with EGR application. Urabe *et al.* (1998) have measured the piston frictional force to investigate the influence of soot contents in recirculated exhaust gas with EGR application on the piston lubricating condition in diesel engines, and have showed that the reduction of sulfur contents in fuel was very effective to decrease the wear, but the wear increased with the soot or water contents in recirculated exhaust gas even though sulfur contents were not included in fuel. They have also demonstrated that the piston frictional force increased sharply by the soot contents in recirculated exhaust gas at the latter half of compression stroke, which may form the abnormal wear.

According to previous studies (Shiozaki and Suzuki, 1990 ; Kano *et al.*, 1987), it has been found that great amounts of soot particulate were deposited on the head part close to the piston crown, and the piston crown part neighboring intake and exhaust valves. The results in the present study may be similar to those of previous works. That is, it can be considered from the results shown in this study that the head parts in case of EGR application made a relatively frequent contact with combustion gases, resulting in great amounts of soot deposit. And the erosion wear increased because H_2SO_4 formed may lead to precipitate formed around soot particles as mentioned above. It is also noted that the abrasion wear may be produced by abrasive powder on the roughened eroded surfaces.

$Ca(OH)_2$ contained in lubricating oil acts as a neutralizing agent to inhibit erosion. Because recirculated exhaust gases with EGR application cause the quick drop of alkali index in lubricating oil and the speedy increase of the insoluble component in normal heptane and resin component, EGR application in a diesel engine may lead to serious deterioration of lubricating oil. Increased soot emissions due to greater EGR rate are mixed

Table 4 The mean outer diameters of piston head and skirt measured before and after the experiment to calculate the wear amounts of two cylinders at two spots of front-rear and right-left

	Piston Head		Piston Skirt	
	No. 1 Cyl. (No EGR)	No. 2 Cyl. (EGR)	No. 1 Cyl. (No EGR)	No. 2 Cyl. (EGR)
Before Exp. (mm)	95.152	95.151	95.778	95.788
After Exp. (mm)	95.177	95.215	95.723	95.726
Wear Amounts (mm)	−0.025	−0.064	0.055	0.062

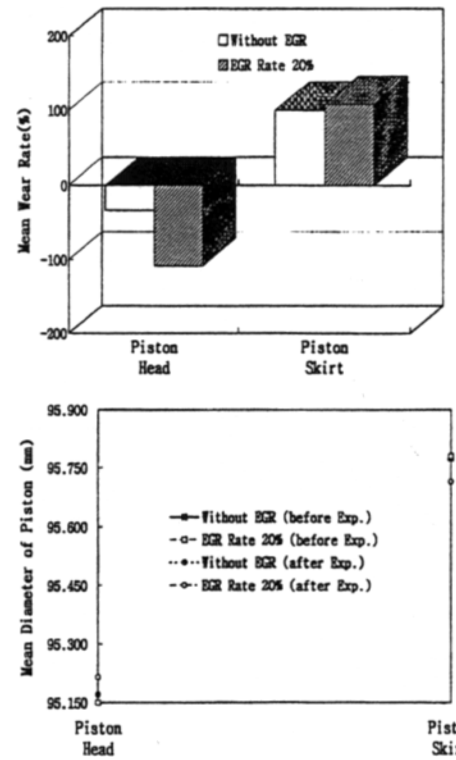


Fig. 9 Mean wear rates and outer diameters of piston head and skirt for two spots of right-left and front-rear at the respective measured positions away from the crown

with lubricating oil to add to the insoluble component in normal heptane; the eroded surfaces of cylinder liner and piston are rubbed with the oxide compound of lubricating oil and soot emissions as an abrasive, resulting in further wear in piston and cylinder liner. (Orii, 1995 ; Lie *et al*., 1996 ; Kitahara *et al*., 1997 ; Sasaki *et al*., 1997 ; Urabe *et al*., 1998 ; Dennis *et al*., 1999 ; Andrews *et al*., 1999)

4. Conclusions

The EGR application in diesel engines poses many problems such as exhaust emissions, fuel economy, durability and so on. However, EGR may be recommended as one of the most effective methods for reducing NO_x emissions because there are few strategies to effectively reduce them. Therefore, many research efforts are necessary to minimize the problems of EGR application. In the present study, a two-cylinder diesel engine was operated with fresh air fed into one cylinder and recirculated exhaust gas of 20% into the other cylinder to investigate the effect of recirculated exhaust gas on the wear of cylinder liner and piston. The major results are as follows:

(1) The mean wear rate of cylinder liner was approximately constant regardless of measuring positions in case of no EGR application, while the mean wear rate with EGR was greater in the second half than the first half.

(2) The mean wear rate of piston skirt part with EGR application was slightly higher than that without EGR. The piston diameter of head part due to soot adhesion and erosion wear increased, particularly more remarkable in case of EGR application.

The present study represented wear rate as length differences measured before and after the experiment. In further studies, however, it may be expected that, though it may not be simple, attempts could be made to measure wear rate as mass differences. In addition, supplementary researches such as analyzing photographs of erosion and wear defect parts, and measuring the soot contents and H_2SO_4 component contained in lubricating oil are also needed.

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